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SYSTEM AND METHOD FOR ADAPTIVE PHASE COMPENSATION OF OFDM SIGNALS

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Cross-Reference to Related Applications

This application is a continuation under 37 C.F.R. 111(a) of International Application Serial No. PCT/RU03/00125, filed March 28, 2003, which is incorporated herein by reference.

This application is related to the following co-pending, commonly assigned U.S. patent applications entitled "RECEIVER AND METHOD TO DETECT AND SYNCHRONIZE WITH A SYMBOL BOUNDARY OF AN OFDM SYMBOL", serial number xx/xxx,xxx, filed on same date herewith, attorney docket number 884.781us1 (P13889), and "SYSTEM AND METHOD FOR TWO-CHANNEL FREQUENCY OFFSET ESTIMATION OF OFDM SIGNALS", serial number xx/xxx,xxx, filed on same date herewith, attorney docket number 884.783us1 (P13891). These commonly assigned patent applications are incorporated herein by reference.

Technical Field

The present invention pertains to wireless communications, and in one embodiment, to receivers for orthogonal frequency division multiplexed (OFDM) communications.

Background

Orthogonal frequency division multiplexing (OFDM) is a multi-carrier transmission technique that uses orthogonal subcarriers to transmit information within an available spectrum. Because the subcarriers may be orthogonal to one another, they may be spaced much more closely together within the available spectrum than, for example, the individual channels in a conventional frequency division multiplexing (FDM) system. To help achieve orthogonality, a subcarrier may have a null at the center frequency of the other subcarriers. Orthogonality of

the subcarriers may help prevent inter-subcarrier interference within the system. Before transmission, the subcarriers may be modulated with a low-rate data stream. The transmitted symbol rate of OFDM symbols may be low, and thus the transmitted OFDM signal may be highly tolerant to multipath delay spread within the channel. For this reason, many modern digital communication systems are turning to OFDM as a modulation scheme for signals that need to survive in environments having multipath reflections and/or strong interference. Many wireless communication standards have already adopted OFDM including, for example, the IEEE 802.11a standard, the Digital Video Broadcasting Terrestrial (DVB-T) standard, and the High performance radio Local Area Network (HiperLAN) standard. In addition, several industry consortia, including the Broadband Wireless Internet Forum and the OFDM Forum, are proposing OFDM for fixed wireless access systems.

One problem with OFDM systems is that they may be more sensitive to phase noise and frequency variation relative to single carrier systems. Unlike single carrier systems, phase noise and frequency variation in OFDM systems introduce interference, including inter-carrier interference and inter-symbol interference. Some conventional OFDM systems use special training symbols and/or phase locked loops (PLLs) for estimating frequency offset and for tracking phase variations, however accurate frequency synchronization and phase compensation using these techniques is especially difficult because of the noise and channel effects, such as linear distortion in a multipath channel. Thus there is a general need for systems and methods that provide frequency synchronization and phase tracking in an OFDM receiver system.

Brief Description of the Drawings

The appended claims are directed to some of the various embodiments of the present invention. However, the detailed description presents a more complete understanding of the present invention when considered in connection with the figures, wherein like reference numbers refer to similar items throughout the figures and:

FIG. 1 is a simplified functional block diagram of an orthogonal frequency division multiplexed (OFDM) receiver system in accordance with an embodiment of the present invention;

FIG. 2 is a functional block diagram of a pilot subcarrier processing unit in accordance with an embodiment of the present invention; and

FIG. 3 is a flow chart of a data symbol phase compensation procedure in accordance with an embodiment of the present invention.

Detailed Description

The following description and the drawings illustrate specific embodiments of the invention sufficiently to enable those skilled in the art to practice it. Other embodiments may incorporate structural, logical, electrical, process, and other changes. Examples merely typify possible variations. Individual components and functions are optional unless explicitly required, and the sequence of operations may vary. Portions and features of some embodiments may be included in or substituted for those of others. The scope of the invention encompasses the full ambit of the claims and all available equivalents.

FIG. 1 is a simplified functional block diagram of an orthogonal frequency division multiplexed (OFDM) receiver system in accordance with an embodiment of the present invention. OFDM receiver system 100 may include radio frequency (RF) receive unit 102, data symbol processing unit 104, short training symbol processing unit 106 and long training symbol processing unit 108. RF receive unit 102 receives signals through antenna 111 and generates serial symbol stream 110 of OFDM symbols. Data symbol processing unit 104 processes serial symbol stream 110 to generate decoded bit stream 140.

In accordance with an embodiment of the present invention, OFDM receiver system 100 may apply phase compensation to subcarriers of the data symbols of an OFDM packet after channel equalization and before symbol demapping. A phase compensation estimate may be generated from pilot subcarriers within the data symbol and applied to the subcarriers of the data symbol prior to demapping. The pilot subcarriers of the data symbol may be combined and weighted to generate an observation vector, and recursive filtering

may be performed on the observation vector to generate the phase compensation estimate. The pilot subcarriers may be weighted based on fading gains to maximize a signal to noise ratio (SNR) of the observation vector. The recursive filtering may include performing extended Kalman filtering (EKF) on the observation vector using a channel estimate, an additive noise power estimate, a signal to noise ratio (SNR) estimate, a transceiver oscillator phase noise power and/or other a priori information determined from dynamic models of the phase. The channel estimate may be generated from a long training symbol of the OFDM packet, and the additive noise power estimate and the SNR estimate may be generated from short training symbols of the OFDM packet. The phase noise power may be evaluated form a priori information about the phase noise spectrum of transceiver oscillators. The channel estimate, the additive noise power estimate, the SNR estimate, and the phase noise power value may be used for subsequent data symbols of the OFDM packet.

An OFDM data packet may be comprised of a plurality of sequential symbol modulated subcarriers. The packet may start with short training symbols, which may use only a portion of the subcarriers. The short training symbols may be followed by a long training symbol and the data symbols. The data symbols may contain known pilot subcarriers. The data symbols may be time multiplexed with data symbols comprising known pilot subcarriers as well as data subcarriers.

In one embodiment, an OFDM packet may comprise approximately fifty-two subcarriers, and in other embodiments, the OFDM packet may comprise up to a hundred or more subcarriers. In one embodiment, an OFDM packet may start with approximately ten short training symbols, and in other embodiments, the OFDM packet may start with as little as one and as many as fifty or more short training symbols. In one embodiment, an OFDM packet may include approximately one long training symbol, and in other embodiments, the OFDM packet may include up to ten or more long training symbols. In one embodiment, the data symbols may contain approximately four known pilot subcarriers, and in other embodiments, the data symbols may contain as little as one and as many as ten or more pilot subcarriers.

OFDM receiver system 100 may be part of a wireless communication device or may be part of a stand-alone receiver. OFDM receiver system 100 may

be part of wireless communication devices such as personal digital assistants (PDAs), laptop and portable commuters with wireless communication capability, web tablets, wireless telephones, wireless headsets, pagers, instant messaging devices, MP3 players, digital cameras, and other devices that may receive and/or transmit information wirelessly. OFDM receiver system 100 may receive communication signals transmitted in accordance with a multi-carrier transmission technique, such as an OFDM technique, which may use substantially orthogonal subcarriers to transmit information within an assigned spectrum. OFDM receiver system 100 may receive communications in accordance with one or more communication standards, such as one of the IEEE 802.11a, b or g standards, the Digital Video Broadcasting Terrestrial (DVB-T) standard, or the High performance radio Local Area Network (HiperLAN) standard. Signal communications in accordance with other local area network (LAN) and wireless local area network (WLAN) communication techniques may also be suitable for receipt by OFDM receiver system 100.

OFDM receiver system 100 may include RF receive unit 102, which receives signals through antenna 111 and generates serial symbol stream 110 of OFDM symbols. Data symbol processing unit 104 processes serial symbol stream 110 to generate decoded bit stream 140. Antenna 111 may be, for example, a dipole antenna, monopole antenna loop antenna, microstrip antenna or other type of antenna suitable for reception and/or transmission of multi-carrier communication signals including OFDM packets. In one embodiment, an OFDM packet may include a plurality of short training symbols and a plurality of long training symbols followed by data symbols.

In one embodiment, the received signal may have a carrier frequency ranging between five and six GHz, although embodiments of the present invention are equally suitable for receipt of carrier frequencies, for example, ranging between one and ten 10 GHz. An OFDM signal may, for example, reside on up to a hundred or more subcarriers. The short training symbols may be transmitted on a portion of the subcarriers, and data symbols may contain one or more known pilot subcarriers although this is not a requirement. In one embodiment, the long training symbols may have a duration of approximately between three and four

microseconds and the short training symbols may have a duration of up to approximately one microsecond.

RF receive unit 102 may perform a two-stage down conversion. RF receive unit 102 may include low-noise amplifier (LNA) 112 and RF down-converter 114. RF down-converter 114 may generate an intermediate frequency (IF) signal using signals from oscillator 116. Oscillator 116 may be fixed frequency heterodyne oscillator. Automatic gain control (AGC) element 118 may adjust a power level for IF down-converter 120 in response to AGC signal 128 from unit 106. IF down-converter (D/C) 120 may generate in-phase (I) signals and quadrature phase (Q) signals at zero frequency using a frequency controllable device such as voltage-controlled oscillator (VCO) 122, which may be responsive to coarse frequency offset signal 107. Coarse frequency offset signal 107 may be a part of a feedback loop and provided by short training symbol processing unit 106. The in-phase (I) signals and quadrature phase (Q) signals, provided by IF down-converter 120, may be sampled and converted to serial digital bit stream 110 by analog to digital converter (ADC) 126. Serial digital bit stream 110 produced by ADC 126 may be a serial symbol stream of OFDM symbols in the case of receipt of an OFDM packet. OFDM system 100 may also include phase rotator 141 may rotate the phase of symbols of stream 110 in response to fine frequency offset estimate 109, which may be generated by long training symbol processing unit 108. In an alternate embodiment, phase rotator 141 may be responsive to frequency-offset estimate 139 provided by data signal processing unit 104.

In one embodiment, short and long training symbol processing units 106 and 108 may perform packet detection and synchronization with OFDM symbol boundaries and may initiate data processing by data symbol processing unit 104. Data symbol processing unit 104 processes serial symbol stream 110 of OFDM symbols to generate decoded bit stream 140. Long training symbol processing element 108 may generate channel estimate 164 from a long training symbol of the OFDM packet for use by data symbol processing unit 104. Short training symbol processing unit 106 may generate an additive noise power estimate and a signal to noise ratio (SNR) estimate 162 from one or more of the short training symbols of the OFDM packet for use by data symbol processing unit 104.

Data symbol processing unit 104 may include serial to parallel converter 142 to convert a symbol from serial symbol stream 110 into parallel groups of time domain samples 144. Data symbol processing unit 104 may also include FFT element 146, which may perform a Fast Fourier Transform (FFT) on parallel groups of time domain samples 144 to generate frequency domain symbol modulated subcarriers 148. In one embodiment, FFT element 146 may be responsive to a fine timing signal. Channel equalizer 154 may perform a channel equalization on frequency domain symbol modulated subcarriers 148 provided by FFT element 146. Channel equalizer 154 may generate channel equalized frequency domain symbol modulated subcarriers 158 using channel estimations 164 generated by long training symbol processing element 108. Channel estimations 164 generated by long training symbol processing element 108 may be made by performing an FFT on known training symbols, such as the long training symbols, before data symbol processing begins. Equalized frequency domain symbol modulated subcarriers 158 may be coherently demodulated by demodulator 150 to produce a plurality of parallel symbols. Demodulator 150 may demodulate the subcarriers in accordance with a particular modulation order in which a transmitter modulated the subcarriers.

Data symbol processing unit 104 may also include pilot subcarrier processing unit 156, which may act as a phase tracking unit to generate phase compensation estimate 157 for a data symbol of the OFDM packet. Pilot subcarrier processing unit 156 may use pilot subcarriers 147 within the data symbol separated within FFT element 146. Data symbol processing unit 104 may also include phase compensator 159 to apply phase compensation estimate 157 to the subcarriers of the data symbol prior to demapping. In one embodiment, pilot subcarrier processing unit 156 may also use channel estimate 164 generated by long training symbol processing element 108. Pilot subcarrier processing unit 156 may also use additive noise power estimate and a signal to noise ratio (SNR) estimate 162 generated by short training symbol processing unit 106 and/or a phase noise power value determined from a priori information about the phase noise spectrum of transceiver oscillators to generate the phase compensation estimate 157. Pilot subcarriers 147 may be separated from other subcarriers 148 of a data symbol during performance of an FFT by FFT element 146.

In accordance with one embodiment of the present invention, phase rotator 141 may rotate the phase of symbols of symbol stream 110 in response to a frequency offset estimate 109 provided by long training symbol processing element 108. In this embodiment, fine frequency offset estimate 109 may be determined from long training symbols of an OFDM packet. The phase-shift provided by phase rotator 141 may be held constant for processing the data symbols of the OFDM packet. In accordance with another embodiment, frequency offset estimate 139 may alternatively be provided to phase rotator 141 by a pilot subcarrier processing element of data symbol processing unit 104. This is described in more detail below.

Although OFDM receiver system 100 is illustrated as having several separate functional elements, one or more of the functional elements may be combined and may be implemented by combinations of software configured elements, such as processors including digital signal processors (DSPs), and/or other hardware elements. Although embodiments of the present invention are described with respect to OFDM communications, embodiments of the present invention may be suitable to any multi-carrier communication technique.

FIG. 2 is a functional block diagram of a pilot subcarrier processing unit in accordance with an embodiment of the present invention. Pilot subcarrier processing unit 200 may generate a phase compensation estimate for use in phase compensating data symbols of an OFDM packet. Pilot subcarrier processing unit 200 may be suitable for use as pilot subcarrier processing unit 156 (FIG. 1) although other processing units may also be suitable. Pilot subcarrier processing unit 200 may use the pilot subcarriers of a data symbol, along with, for example, a channel estimate, an additive noise power estimate, a signal to noise ratio (SNR) estimate, and/or a phase noise power value for generating the phase compensation estimate. The phase compensation estimate may be generated for data symbols of the OFDM packet and may be applied after performing an FFT on the subcarriers. The phase compensation estimate may also be applied after channel equalization of the data subcarriers. The phase compensation estimate may be used for phase tracking data symbols during processing of the OFDM packet. In one embodiment, pilot subcarrier processing unit 200 may also generate a frequency offset estimate for use in phase rotating a serial symbol stream prior to performing

the FFT. Although pilot subcarrier processing unit 200 is illustrated as having several separate functional elements, one or more of the functional elements may be combined and may be implemented by combinations of software configured elements, such as processors including digital signal processors (DSPs), and/or other hardware elements. In an embodiment, pilot subcarrier processing unit 200 may operate as a phase tracking unit for use in phase compensating data symbols in an OFDM receiver system.

Pilot subcarrier processing unit 200 includes observation vector former 204 which may weight and combine pilot subcarriers 202 to generate observation vector 206. Pilot subcarriers 202 may be comprised in-phase (I) and quadrature phase (Q) signal components. Recursive filter 208 operates on observation vector 206 to generate phase compensation estimate 212. Pre-calculation unit 210 may recalculate fading gains 205 (e.g., channel estimates), and noise information and estimates 207. Noise information and estimates 207 may include at least one of an additive noise power estimate, SNR estimates, and a noise power value for use by recursive filter 208 in generating phase compensation estimate 212.

Observation vector former 204 includes weighting element 214 which may weight pilot subcarriers 202 based on fading gains 205 for pilot subcarriers 202 prior to combining the weighted subcarriers in combining element 216 to generate observation vector 206. Reduction element 218 may reduce the magnitude of the observation vector depending on the number of pilot subcarriers combined in element 216. For example, when four subcarriers are combined, element 218 may apply a magnitude reduction of ¼ to observation vector 206. In one embodiment, observation vector former 204 may generate an observation vector for data symbols of an OFDM packet from the pilot subcarriers of the packet.

In one embodiment, fading gains 205 may be generated from a channel estimate determined from long training symbols of the OFDM packet. In this embodiment, weighting element 214 may apply weights individually to pilot subcarriers. The weights may be complex conjugates of the fading gains of the pilot subcarriers. In one embodiment, the weights may also be calculated for pilot subcarriers to help maximize a signal to noise ratio (SNR) of observation vector 206. Pilot subcarriers 202 may be unequalized and may be separated from other subcarriers of a data symbol during performance of an FFT by an FFT element,

such as FFT element 146 (FIG. 1). In one embodiment, channel equalizer 154 may equalize pilot subcarriers 202.

In one embodiment, recursive filter 208 may perform an extended Kalman filtering (EKF) process on the observation vector using a channel estimate, an additive noise power estimate, a signal to noise ratio (SNR) estimate, transceiver oscillator phase noise power value, and/or other a priori information from a dynamic model of the phase. The channel estimate may be generated from long training symbols of the OFDM packet, and the additive noise power estimate and the SNR estimate may be generated from short training symbols of the OFDM packet. The phase noise power value may be evaluated from a priori information about the phase noise spectrum of transceiver oscillators. In one embodiment, the channel estimate, the additive noise power estimate, the SNR estimate, and the phase noise power value may be used by recursive filter 208 for all data symbols of the OFDM packet.

Recursive filter 208 may include subtraction element 220 to subtract predicted observation vector 222 from observation vector 206 to generate residual vector 224. Recursive filter 208 may also include multiplication element 226 to multiply residual observation vector 224 by gain matrix result 228 to generate residual gain vector 230. Addition element 232 may add residual gain vector 230 to linear prediction vector 234 to generate estimate vector 236. Estimate vector 236 may be a multi-dimensional vector comprised of a frequency offset estimate and phase compensation estimate 212. The dimension of estimate vector 236 may depend on the dimension of a state equation used to dynamically model the phase. The frequency-offset estimate may be applied to phase rotator 141 (FIG. 1) to rotate a phase of a serial symbol stream comprising the data symbols prior to performing the FFT on the data symbols. Phase compensation estimate 212 may be applied to a data symbol subsequent to the FFT. The frequency offset estimate and phase compensation estimate 212 may be extracted from the estimate vector 236. The frequency-offset estimate may be provided to a phase rotator, such as phase rotator 141 (FIG. 1) as frequency offset estimate 139.

Current observation vector 206 may be represented as vector $z(k+1)$, predicted observation vector 222 may be represented as vector $h[x(k+1 \mid k)]$,

residual vector 224 may be represented as vector $\tilde{z}(k+1)$, gain matrix result 228 may be represented as matrix K(k+1), residual gain vector 230 may be represented as vector $K(k+1)\tilde{z}(k+1)$, linear prediction vector 234 may be represented as vector $\hat{x}(k+1|k)$, and estimate vector 236 may be represented as vector $\hat{x}(k+1)$. "k" may represent a particular data symbol of the plurality of data symbols of an OFDM packet, wherein an iteration of the filter, k may be incremented by one. Phase compensation estimate 212 may be represented as $\hat{\theta}(k+1)$, extracted from estimate vector 236 $\hat{x}(k+1)$.

In an alternate embodiment, observation vector 206 may include the four complex values comprising the quadrature components of the pilot subcarriers quadrature components. This alternate embodiment, however, may lead to larger dimension (e.g., an 8x8) matrix computation by calculation block 240.

Recursive filter 208 may also include one time step delay element 238 which may store previous step estimate vector 236 $\hat{x}(k)$ for use by calculation block 240 in generating linear prediction vector 234 and gain matrix 228. In another embodiment, one-time step-delay element 238 may be placed after linear prediction element 242 and may store linear prediction vector 234 $\hat{x}(k+2|k+1)$, provided by linear prediction element 242. Extracted from linear prediction vector 234, a frequency-offset estimate may be used by phase rotator 141 for rotating next (k+2) data symbol prior to performing the FFT.

Calculation block 240 receives recalculated fading gains, an additive noise power estimate, an SNR estimate and a phase noise power value from pre-calculation unit 210. Calculation block 240 may be designed in accordance with a dynamic model of the phase and may include linear prediction element 242, error covariance matrix evaluation element 244, gain matrix evaluation element 246 and signal vector evaluation element 248.

In one embodiment, recursive filter 208 may generate an estimated phase for the present symbol (e.g., the k+1 symbol) based on pilot subcarriers of a present symbol (e.g., the k+1 symbol) and previous value of multi-dimensional estimate vector 236. In this embodiment, referred to as a feed-forward scheme, a phase compensation estimate may be used by phase compensator 159 after performing an FFT. In another embodiment, recursive filter 208 may generate a

predicted frequency offset and phase for a next data symbol (e.g., the k+2 symbol) based on pilot subcarriers of a present symbol (e.g., the k+1 symbol). In this embodiment, referred to as a feedback scheme, a frequency-offset estimate may be used in phase rotator 141 for the next data symbol (e.g., the k+2 symbol) prior to performing the FFT.

In one embodiment, pre-calculation block 210 recalculates fading gains, additive noise power estimates, SNR estimates (e.g., received from the short and/or long training symbol processing blocks), and a phase noise power value (e.g., from a priori information about the phase noise spectrum of transceiver oscillators) to help optimize parameters for recursive filter 208. Recursive filter 208 may be an Extended Kalman Filter (EKF) or other suitable recursive filter.

For a received packet, pre-calculation block 210 may calculate a variance of the additive noise in the observation model. The variance of the additive noise may be calculated from the additive noise power estimate done by the short training symbol processing block, and the fading gains done bye the long training symbol processing block. The values of the variances of the additive noise may be equal to the additive noise powers corresponding to pilot subcarriers. Accordingly, pilot subcarriers may have a different value for the variance of additive noise. From the values of the variance of the additive noise, a covariance matrix of the observation model noise may be generated and provided to errors covariance matrix evaluation element 244. In one embodiment, this covariance matrix of the observation model noise may be a diagonal matrix with equal elements. In other embodiments, elements of this matrix may be different. The dimension of the covariance matrix of the observation model noise may depend on the dimension of observation vector 206. Elements of the covariance matrix of the observation model noise may be used for performing a recurrent algorithm by errors covariance matrix evaluation element 244. Elements of the covariance matrix of the observation model noise may also be used for performing a recurrent algorithm by gain matrix evaluation element 246 for an iteration of filter 208.

For a received packet, pre-calculation block 210 may also calculate a variance of the additive noise in the dynamic model of the phase for use by recursive filter 208. This variance may be calculated from a priori information about phase noise spectrum of transceivers oscillators. The value of this variance

may be used by errors covariance matrix evaluation element 244 for an iteration of filter 208. From this value, a covariance matrix of the noise in the state equation representing the dynamic model of the phase may be formed. The dimension of this matrix may depend on the dimension of a state equation (e.g., a phase system model). In one embodiment, this covariance matrix of the noise in the state equation may be 2x2 matrix with at least one nonzero element. In other embodiments, the dimension and values of elements of this matrix may differ.

For a received packet, pre-calculation block 210 may also calculate an initial (e.g., a priori) variance of the frequency offset after the phase rotator. The initial variance may be calculated from SNR estimate 207 generated by the short training symbol processing block. In other embodiments, the initial variance of frequency offset may be calculated by the long training symbol processing block.

For a received packet, pre-calculation block 210 may also calculate an a priori variance of the initial phase error. This variance may be calculated from SNR estimate 207 and from information about phase noise spectrum of transceiver oscillators. These two variances may be used for initially forming a covariance matrix, which may be used as an initial condition by errors covariance matrix evaluation element 244 at the first iteration of recursive filter 208.

For a received packet, pre-calculation block 210 may also calculate parameters of a vector signal function $\mathbf{h}[\mathbf{x}(k)]$ in the vector observation model for recursive filter 208. The parameters may be calculated from fading gains 205 of pilot subcarriers. Parameters of the vector signal function $\mathbf{h}[\mathbf{x}(k)]$ may be used for performing a recurrent algorithm by errors covariance matrix evaluation element 244, for performing a recurrent algorithm by gain matrix evaluation element 246, and for performing a recurrent algorithm by signal vector evaluation element 248, for an iteration of recursive filter 208.

Linear prediction element 242 may perform a one-step prediction $\tilde{\mathrm{x}}(\mathrm{k}+1 \mid \mathrm{k})$ for the state vector $\mathrm{x}(\mathrm{k})$ (e.g., vector 236) on the basis of a known state equation (e.g., the dynamic model of the phase) and previous step estimate vector 236 $\hat{\mathrm{x}}(\mathrm{k})$ from one-time step-delay element 238. In another embodiment (e.g., a feedback scheme), which may place one time step delay element 238 after

linear prediction element 242, linear prediction vector element 242 may perform a one-step prediction $\hat{x}(k+2 \mid k+1)$ based on present estimate vector 236 $\hat{x}(k+1)$.

FIG. 3 is a flow chart of a data symbol phase compensation procedure in accordance with an embodiment of the present invention. Data symbol phase compensation procedure 300 may be used to generate phase compensation estimates for individual data symbols of an OFDM packet. Procedure 300 may be performed by OFDM receiver system 100 (FIG. 1) although other systems may also be suitable for performing procedure 300. Portions of procedure 300 may also be performed by pilot subcarrier processing unit 156 (FIG. 1) although other pilot subcarrier processing units may also be suitable. Although the individual operations of procedure 300 are illustrated and described as separate operations, one or more of the individual operations may be performed concurrently and nothing requires that the operations be performed in the order illustrated.

Operation 302 performs an FFT on a serial symbol stream (e.g., time-domain symbol modulated subcarriers) to generate frequency domain symbol modulated subcarriers. Some of the frequency-domain symbol modulated subcarriers may be pilot subcarriers of a data symbol of an OFDM data packet. In one embodiment, operation 302 may perform a FFT on parallel groups of time domain samples 144 (FIG. 1) to generate frequency domain symbol modulated subcarriers 147, 148 (FIG. 1). Operation 304 may separate pilot subcarriers 147 (FIG. 1) from other subcarriers 148 (FIG. 1) of a data symbol.

Operation 306 weights and combines the pilot subcarriers to generate an observation vector. In one embodiment, operation 306 may weight pilot subcarriers based on fading gains from channel estimate 307 for the pilot subcarriers prior to combining the weighted subcarriers to generate the observation vector. Operation 306 may be performed, for example, by observation vector former 204 (FIG. 2).

Operation 308 may perform recursive filtering on the observation vector to generate a phase compensation estimate for a data symbol. Operation 308 may use channel estimate 307 along with SNR and additive noise power estimates 309, and a priori information 311. A priori information may include information about the phase noise spectrum of transceiver oscillators and/or a dynamic model of the phase. In one embodiment, channel estimate 307 may be generated from one or

more long training symbols of the OFDM packet. SNR and additive noise power estimates 309 may be generated from one or more of the short training symbols of the OFDM packet. The phase noise power value may be evaluated from a prior information about the phase noise spectrum of transceiver oscillators. In one embodiment, channel estimate 307, SNR and additive noise power estimate 309, and the phase noise power value may be used in determining the phase compensation estimates for substantially most or all data symbols of the OFDM packet. Operation 308 may be performed, for example, by recursive filter 208 (FIG. 2).

Operation 310 compensates phases of the subcarriers of a data symbol using the phase compensation estimate generated in operation 308. Operation 310 may be performed by phase compensator 159 (FIG. 1). Operation 312 may de-map and/or decode the phase compensated subcarriers of the data symbol to generate a portion of a decoded bit stream. Operation 314 repeats at least operations 306 through 312 for subsequent data symbols of an OFDM packet to generate other portions of a decoded bit stream. During the repetition of operations 306 through 312, operation 302 may continue performing an FFT on the serial symbol stream and operation 304 may continue separating out the pilot subcarriers of data symbol of an OFDM packet.

Thus, improved systems and methods for phase compensating data symbols of an OFDM packet have been described. The systems and methods of the present invention may provide for faster phase tracking convergence, as well as higher phase estimate precision over conventional PLL systems. Further, reduced complexity and cost of the analog portions of the OFDM receiver may be achieved because of the higher phase tracking performance, which may allow for the reduction in stability and phase noise requirements of the receiver and/or transmitter oscillators.

The foregoing description of specific embodiments reveals the general nature of the invention sufficiently that others can, by applying current knowledge, readily modify and/or adapt it for various applications without departing from the generic concept. Therefore such adaptations and modifications are within the meaning and range of equivalents of the disclosed embodiments. The phraseology or terminology employed herein is for the purpose of description and not of

limitation. Accordingly, the invention embraces all such alternatives, modifications, equivalents and variations as fall within the spirit and scope of the appended claims.